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Water quality of surface runoff and lint yield in cotton under furrow irrigation in Northeast Arkansas

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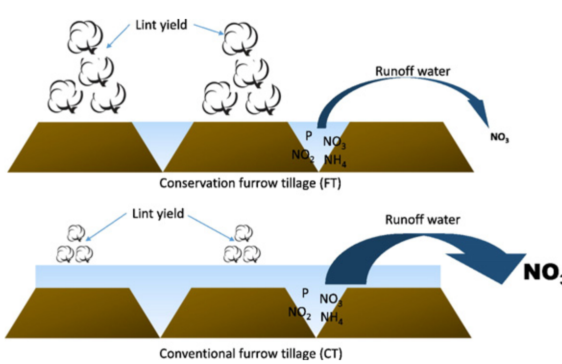
HIGHLIGHTS

- Intensity and chemical form of nutrient losses were mainly controlled by volume of water runoff and agronomic practice.
- Nitrate was the highest N form in runoff water.
- Lint yields increased through improved furrow tillage irrigation and adequate N rate application.
- This information helps stakeholders develop efficient cropping systems that minimize water pollution and sustain high yield.

GRAPHICAL ABSTRACT



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ABSTRACT

Use of furrow irrigation in row crop production is a common practice through much of the Midsouth US and yet, nutrients can be transported off-site through surface runoff. A field study with cotton (*Gossypium hirsutum*, L.) was conducted to understand the impact of furrow tillage practices and nitrogen (N) fertilizer placement on characteristics of runoff water quality during the growing season. The experiment was designed as a randomized complete block design with conventional (CT) and conservation furrow tillage (FT) in combination with either urea (URN) broadcast or 32% urea ammonium nitrate (UAN) injected, each applied at 101 kg N ha^{-1}. Concentrations of ammonium (NH_4-N), nitrate (NO_3-N), nitrite (NO_2-N), and dissolved phosphorus (P) in irrigation runoff water and lint yields were measured in all treatments. The intensity and chemical form of nutrient losses were primarily controlled by water runoff volume and agronomic practice. Across tillage and fertilizer N treatments, median N concentrations in the runoff were <0.3 mg N L^{-1}, with NO_3-N being relatively the highest among N forms. Concentrations of runoff dissolved P were <0.05 mg P L^{-1} and were affected by volume of runoff water. Water pH, specific electrical conductivity, alkalinity and hardness were within levels that common to local irrigation water and less likely to impair pollution in waterways. Lint yields averaged 1111 kg ha^{-1} and were higher (P-value = 0.03) in FT compared to CT treatments. Runoff volumes across irrigation events were greater (P-value = 0.02) in CT than FT treatments, which increased NO_3-N mass loads in CT treatments (394 g NO_3-N ha^{-1}-season^{-1}). Nitrate-N concentrations in CT treatments were still low and pose little threat to N contaminations in

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waterways. The findings support the adoption of conservation practices for furrow tillage and N fertilizer placement that can reduce nutrient runoff losses in furrow irrigation systems.

1. Introduction

Arkansas ranks third in irrigated acreage among US states (USDA NASS, 2013). In 2012, approximately, 10.4% of 1.94 M ha of irrigated cropland in Arkansas was planted in cotton. About 80% of this cotton was irrigated at least once during the growing season. Cotton production in Arkansas, Texas and Georgia comprised 53% of cotton produced, representing about 51% of the value of US cotton and cottonseed sales in 2012 (USDA NASS, 2013).

Arkansas cotton is typically produced using conventional furrow irrigation (roughly 50% of total irrigated fields) (USDA NASS, 2013). Plants are grown on raised beds with plastic pipe (polytube) used to deliver water into small channels or "furrows" constructed along the primary direction of field slope (Walker, 2003). While furrow irrigation effectively delivers water to the crop, flowing water can transport nutrients, sediments, salts, trace elements, microbes and other solutes to off-site locations through surface runoff. Sediment losses may range from near zero to >100 Mg ha^{-1} for surface-irrigated crops (Carter, 1990). Bjorneberg et al. (2006) reported surface runoff from furrow irrigated fields in Kimberly, Idaho, contained mean dissolved reactive P (DRP) concentrations from 0.04 to 0.10 mg L^{-1} and total P (TP) from 0.3 to 12.5 mg L^{-1}. Additionally, TP was linearly correlated to runoff suspended sediment. Lentz and Lehrsch (2010) found nutrient concentrations (mg L^{-1}) in runoff from furrow-irrigated maize in Kimberly, Idaho, ranged from (i) NO_3-N: 0 to 4.07, (ii) NH_4-N: 0 to 2.28, (iii) K: 3.6 to 46.4, (iv) DRP: 0.02 to 14.3 and TP: 0.03 to 41.5. They concluded 2.7% of total urea-N applied and 1.5% of total manure added were lost in irrigation runoff. Similarly, Cessna et al. (2001) estimated 2.2% of TP and 1.9% of ammonium nitrate applied as fertilizer was lost in flood-irrigated cropland in southern Saskatchewan, Canada. Recognizing the relative contribution of irrigation runoff on nutrient transports and accumulations, runoff from agricultural fields remains a key source of contamination and non-point source pollution in waterways (USEPA, 2000).

Although mean annual rainfall in Arkansas often exceeds 1000 mm, most precipitation occurs during winter and spring months. As a result, irrigation is often applied to summer row crops to increase yield potential. The primary source of irrigation water in the region is the Mississippi River Valley Alluvial Aquifer. However, irrigation withdrawals exceed aquifer recharge in portions of Arkansas (Fugitt et al., 2011). To reverse the declining groundwater supply, mitigating approaches such as water conservation practices (i.e. conservation tillage, computerized hole selection) and water reuse (i.e. tailwater recovery, reservoirs) are being recommended and evaluated in the region (Vories and Evett, 2014; USDA NRCS, 2011).

Much of furrow irrigation research conducted in cotton fields has focused on water use efficiency and reduction of surface runoff. Many of these studies reported total water savings from various furrow irrigation strategies (i.e. wide- or narrow-spaced furrow irrigation schemes) ranged from 12 to 22.5% (Stone and Nofziger, 1993; Webber et al., 2008; Subramani and Martin, 2012). In a study of furrow irrigation, Rice et al. (2001) reported runoff was reduced, but deep percolation increased when alternate row irrigation was used in a surface irrigated cotton production system. Although total water savings from these innovative irrigation strategies have been widely studied and recognized as an important driver in effective irrigation management, nutrient losses and water quality associated with tillage and crop practices have not been examined under these irrigation systems. In the MidSouth US, most of the studies that have evaluated water quality of surface water were conducted in on-farm storage reservoirs (i.e. Moore et al., 2015) or watersheds in which the main purpose was to produce baseline monitoring information and/or watershed characterization (i.e. Turner and Rabalais, 2004). Given the limited irrigation-related research in the region (Vories and Evett, 2014; Clary et al., 2012), measuring nutrient losses and water quality of irrigation runoff is needed to substantiate and improve conservation practices that aim to sustain crop yields while minimizing nutrient runoff losses. This experiment was conducted to understand the impact of furrow tillage treatments and N fertilizer placements on water quality characteristics of surface runoff quality and lint yield in irrigated cotton. Specific objectives were to determine the greatest nutrient losses from irrigation runoff during the growing season, as well as relate water quality parameters and lint yield to tillage and fertilizer placement.

2. Materials and methods

2.1. Field experiment

This study was conducted in 2016 at the Judd Hill Foundation Research Farm, Trumann, Arkansas (33.60 N; 90.53 W; elevation 65 m above mean sea level [amsl]). Crop management details are reported in Table 1. The experiment utilized a 2 × 2 factorial arranged in a randomized complete block with three replications. Furrow tillage treatments were conventional (CT) and conservation furrow tillage (FT), and N fertilizer treatments were either urea broadcast (URN) on the surface soil or 32% urea ammonium nitrate (UAN) applied side-dress. The rate of both fertilizer treatments was 101 kg N ha^{-1}. Plots were eight rows, 0.97 m wide and 162 m long (Fig. 1).

Cotton cultivar ST 4946GLB2 was seeded at 9 seeds m^{-1} of row on 28 Apr 2016 into a Dundee silt loam (Table 2). Prior to planting, raised beds were re-formed with disk-bedders and then the tops smoothed using a field cultivator fitted with rolling baskets. On 14 June, 47 days after planting (DAP), UAN or URN was applied, and the following day, water furrows were cleared using either a conventional sweep plow (Buffalo cultivator) or a "conservation" plow (Furrow Runner). The Furrow Runner features 51 cm (20 in.) scalloped disc furrowers, a shovel plot and a steel packer wheel (www.perkinsales.com/page3.html#furrowrunner).

Treatment assessments included weekly plant monitoring using COTMAN (Oosterhuis et al., 2008) as well as a drop cloth sampling for tarnished plant bug (*Lygus lineolaris*). COTMAN Squaremap sampling protocols included counts of number of main stem squaring nodes, first position square and boll retention and plant height for five consecutive plants on two adjacent rows in two points per treatment plot. COTMAN Bollman sampling included counts of Nodes Above White

Table 1
Crop management details including dates of planting, fertilizer application, tillage practices, irrigation and harvest timing.

Operation	Date	Days after planting
Date of planting	28 April 2016	0
N fertilizer application	14 June	47
Water furrows cleared	15 June	48
Irrigation	17, 24 June; 7, 14, 21, 29 July; 5 August	50, 57, 70, 77, 84, 92, 99
Harvest	29 September	154

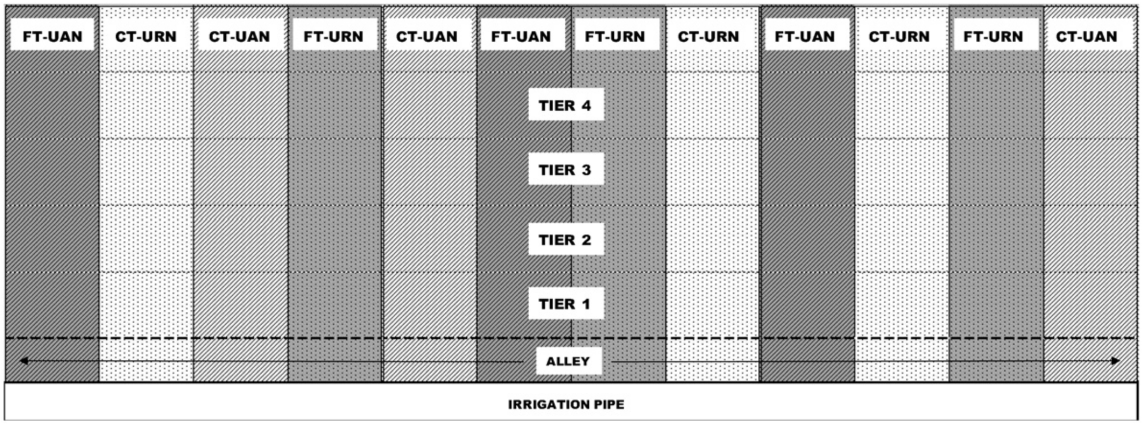

Fig. 1. Field layout of four tillage and N fertilizer placement treatments (FT = Furrow tillage, CT = Conventional plow, URN = urea broadcast, UAN = 32% urea ammonium nitrate injected) during the 2016 growing season.

Flower (NAWF) for ten plants per plot in two points per treatment. Soil water content was monitored using three moisture Watermark sensors, (Irrometer, CA) in each plot placed at 15 and 30 cm depths between plants at the center beds of tillage treatment plots in one replicate. Hanson dataloggers (Mike Hansen Co., Wenatchee, WA) were used to record soil moisture sensor measurements. Rainfall and temperature data were collected from a weather station located at the Judd Hill Foundation Research Farm (www.weather.asu.edu).

Cotton was irrigated during squaring through effective flowering and early boll fill (Table 1). Timing was typically at weekly intervals and was triggered when soil water potential measurements for Watermark sensors at 15 cm depth exceeded 40 centibars (cb). Irrigation water was delivered using 38 cm internal diameter (ID) × 10 mil thickness poly tubing (flexible poly-pipe).

2.2. Water sampling and analysis

After cotton emergence, 3-m wide plants were hand-removed to create alleyways at 24 m intervals through the field. These alleyways facilitated within-field sampling activities. At the edge of plots, bubbler water level recorders, H-flumes and automated water samplers were installed. After each rainfall or irrigation-event, runoff samples were collected from the H-flume using an automated water sampler (6712, Teledyne ISCO) powered by a 12-volt deep cycle marine battery (Interstate SRM-27). The battery was charged using an Alt-E 20 watt solar panel with a 12-volt, 4.5-amp charge regulator. The automated sampler and battery were both housed in a weather-resistant shelter located at the lower field edge of each treatment plot. Once the threshold flow of 21 L min^{-1} was reached, the sampler pumped 200 mL runoff water aliquots into a 10-L composite sample bottle. Water depth in the flume was measured continuously with a water level bubbler in the flume and used to calculate discharge rate. These instruments began collecting data once a flow rate of 21 L min^{-1} occurred. During an irrigation event, the data were collected from the sensors at regular intervals and stored onto the datalogger. Sampler configuration was intended to collect samples throughout a runoff event, preventing over- or under-sampling. Only eight ISCO samplers were available for deployment, and these were installed to cover two replicate blocks. Water samples from the remaining replicate block (four plots) were manually collected at the flume at 1 h and 3 h after runoff began.

Following collection, water samples were stored on ice and transported back to the Delta Water Quality Research Laboratory, DWMRU, USDA-ARS, Jonesboro, Arkansas. Within 24 h of collection, water samples were filtered with a 0.45-μm cellulose acetate syringe filter and stored frozen for about 1 to 7 days prior to chemical analyses. Water samples were analyzed for NH_4-N, NO_3-N, NO_2-N (Doane and Horwath, 2003) (limit of detection is 0.01 mg N L^{-1}), and PO_4-P (hereafter called dissolved P concentration) using ascorbic acid molybdenum blue method modified from Murphy and Riley (1962) with a lower detectable limit of 0.01 mg P L^{-1} (APHA, 1999). Water pH and electrical conductivity were measured using a combination pH/EC electrode and meter (Orion Star A215 Thermo Scientific, Beverly, MA). Hardness and alkalinity were measured in water samples using the titrimetric and potentiometric methods, respectively (APHA, 1999).

2.3. Field and initial soil analyses

Prior to initiating field experiments, soil samples were taken from 0 to 0.30 m soil layer and sent to the Soil and Plant Testing Laboratory, University of Missouri Extension for physical and chemical analyses. Results of analyses are summarized in Table 2. Yield determinations were made using a two-row cotton picker in designated harvest rows. Additional hand-picked samples were collected for yield analysis. Lint yields were taken from Tiers 3 and 4 of the treatment strip (Fig. 1) because of within field variability, particularly in the upper portion of the field where most cotton plants had been diagnosed with *Verticillium* wilt (caused by the soil borne fungus, *Verticillium dahlia*).

2.4. Data analysis

Nutrient concentrations and other water quality metrics were calculated and expressed as mg L^{-1}. Nitrogen and dissolved P mass loads were calculated by multiplying water flow volume by nutrient concentrations, while flow-weighted nutrient concentrations were calculated by dividing the total nutrient mass by the total flow volume. Water samples collected at 1 h and 3 h after runoff were analyzed separately for

Table 2
Soil classification and characteristics of study field.

	Study field
Soil classification	Fine-silty, mixed, active, thermic Typic Endoaqualfs
Soil type	Dundee silt loam
Soil texture, g kg^{-1}	
Sand	400
Silt	475
Clay	125
Chemical properties	
pH	6.1
Specific electrical conductivity, μS cm^{-1}	105
Cation exchange capacity, cmol kg^{-1}	8.8
Extractable Olsen P, mg kg^{-1}	28
Total Organic C, g kg^{-1}	21.5

water quality analyses. Water quality data from this non-automated sampling were pooled after no significant differences were found between time of sampling in each irrigation event (P-value = 0.12–0.95).

All data were subjected to normality tests using the Shapiro-Wilk approach and data that failed normal distributions were either log transformed or analyzed using a nonparametric procedure. Treatment mean (geometric or arithmetic) differences of measured lint yield, nutrient levels and other water quality metrics among tillage and N fertilizer treatment combinations were analyzed using PROC MIXED with protected LSD for multiple mean comparisons or Kruskal-Wallis and Mann-Whitney tests at $P < 0.05$ (SAS, 2010).

3. Results and discussions

3.1. Weather, irrigation, plant monitoring and yield

Throughout the growing season (Apr to Sep), mean daily air temperature ranged from 9.8 to 36.7 °C, with warmest air temperature occurring in July (Fig. 2). Night-time temperatures in the first two weeks after planting were suboptimal in 2016, ranging from 9.4 to 15 °C and those cool temperatures impacted emergence and early season plant growth. First flowers were observed approximately 6 days later than expected (66 DAP) in all treatments (data not shown).

Total seasonal rainfall was 488 mm, which was 12% below the 5-yr average precipitation in this area (www.weather.asu.edu). There were seven irrigation events, and irrigation water was applied at a rate of 199 to 335 m^3 $event^{-1}$. The duration of irrigation application was similar to both furrow tillage treatments and ranged from 6 to 14 h. In each irrigation event, total amount of runoff per irrigation event in FT treatments ranged from 6 to 20 mm $event^{-1}$ while total amount of runoff per irrigation event in CT treatments ranged from 13 to 45 mm $event^{-1}$ (Table 3). There was one heavy rain (>50 mm) recorded on 14 Sep at the study site, during the cropping season (Fig. 2).

No differences for plant monitoring measurements were noted among tillage and fertilizer treatments; this included COTMAN measurements of nodal development, first position square and boll retention, and maturity, measured as days to physiological cutout (NAWF = 5) (data not shown). Key insect pest levels were at low ranges all season, and there were no differences in pest abundance or pest related damage noted among treatments (data not shown).

Lint yields ranged from 823 to 1582 kg ha^{-1} with a mean yield of 1111 kg ha^{-1} ± 20 kg ha^{-1}. Yields were comparable to state averages in 2016, but they were lower than expected. Cool, wet conditions in August and suboptimal temperatures in early season likely had negative

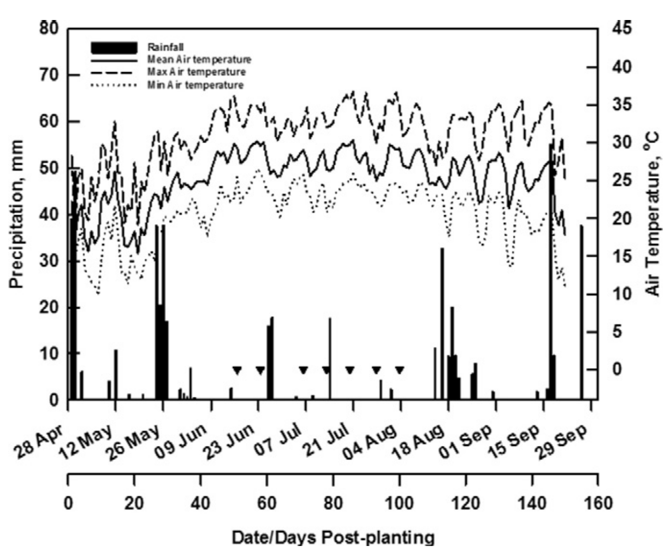

Fig. 2. Daily rainfall, temperature and irrigation events (▼) during the growing season.

impacts on yield potential (Fig. 2; Bourland et al., 2016; Pettigrew, 2002). Disease pressure, particularly *Verticillium* wilt and target spot, were considered a typically severe for northeast Arkansas in 2016 and may have contributed to yield variability; however, no direct measurements of disease damage were made in this field study. Interaction effects of tillage and fertilizer N treatments did not influence (P-value = 0.84) lint yields (Fig. 3) and as well, fertilizer N source and placement had little or no impact on yields (P-value = 0.37). Between tillage treatments, lint yields were highest in FT treatments (P-value = 0.03). Bauer et al. (2010) reported higher lint yields in conservation tillage compared to conventional tillage and suggested greater yields were due to increased water infiltration and decreased soil evaporation, particularly during drought years. In contrast, researchers have found no differences in lint yields between conventional and minimum tillage (Buman et al., 2005; Triplett et al., 1996) or even lower lint yield under ridge tillage (Kennedy and Hutchinson, 2001). Authors attributed yield responses to either weather, soil type, early-season crop growth rate, or root growth impedance. In our study, differences in yield may have been associated with irrigation system performance in the FT treatment (as discussed below).

3.2. Nutrient concentrations in surface water runoff

There was variation in total water volume delivered with each irrigation event which affected concentrations of N and P in irrigation water runoff among tillage and fertilizer N treatments during the growing season. Across study treatments, median flow-weighted concentrations of soluble nutrients were highest in NO_3-N and ranged from 0.162 to 0.343 mg NO_3-N L^{-1}. Other nutrients such as NH_4-N, NO_2-N and dissolved P ranged from 0.069 to 0.193 mg NH_4-N L^{-1}, 0.016 to 0.062 mg NO_2-N L^{-1} and 16 to 52 μg P L^{-1}, respectively (Table 3). These nutrient runoff concentrations were below nutrient values reported for reservoirs and ditch canals in Poinsett County, AR, USA (Moore et al., 2015) and below that of the irrigation water in this study (Table 4). Lower concentrations of dissolved P in runoff water than irrigation water may have been attributable to P being utilized by cotton plants. Since no fertilizer P was applied in all treatments, the observed level of dissolved P in the irrigation water reflected adequate available plant P uptake for crop growth.

Although NO_3-N concentrations were highest among the nutrients tested, flow-weighted concentrations of NO_3-N and NO_2-N in our study were considerably below of 2.90 mg NO_2 + NO_3-N L^{-1} for USEPA Ecoregion X streams subecoregion 73 which includes the Mississippi Alluvial Plain that includes portions of Missouri, Tennessee, Arkansas, Mississippi and Louisiana (USEPA, 2001). In contrast, runoff concentrations of dissolved P exceeded the 20 μg water soluble P L^{-1}, which is the critical P concentration associated with accelerated eutrophication of lakes and impoundments (Hart et al., 2004). However, concentrations of dissolved P in this study were below the USEPA Ecoregion X (Mississippi Alluvial Plain and Western Gulf Coastal Plain) background levels for lakes (60 μg L^{-1}) or rivers (128 μg L^{-1}) (USEPA, 2001).

Nutrient concentrations in runoff water were not different among tillage × fertilizer N treatments (P-value = 0.34–0.83) or between tillage treatments (CT vs FT) (P-value = 0.22–0.85), indicating tillage treatments or the interaction of tillage and fertilizer N placement had no observable effects on N and P runoff concentrations. Across all irrigation events, larger amounts of N and P occurred (P-value ≤0.0001) on 17 Jun when irrigation water was applied three days after N fertilizer application (Fig. 4, Table 1). In the case of dissolved P, higher amounts of runoff water occurred in both tillage treatments, causing more P in runoff water at this early growth stage (Table 3). Likewise, higher levels of N runoff were measured on 5 Aug when the final irrigation was applied (P-value ≤0.0001) (Fig. 4, Table 1). Large concentrations of N runoff measured during the last in-season irrigation event coincided with higher amounts of runoff water, particularly in CT treatments

Table 3
Seasonal median flow-weighted concentrations of ammonium, nitrate, nitrite and water P and water quality metrics in runoff from various tillage and N fertilizer treatments.

Water metrics[a]	Conventional tillage		Furrow tillage	
	Broadcast urea (CT-URN[b])	Injected 32% UAN (CT-UAN[b])	Broadcast urea (FT-URN[b])	Injected 32% UAN (FT-UAN[b])
A. Water quality				
Ammonium-N, mg N L^{-1} $season^{-1}$	0.135 (0.13–0.22)	0.130 (0.10–0.15)	0.193 (0.17–0.61)	0.096 (0–0.12)
Nitrate-N, mg N L^{-1} $season^{-1}$	0.162 (0.10–0.77)	0.322 (0.22–0.44)	0.343 (0.18–0.35)	0.227 (0.07–0.30)
Nitrite-N, mg N L^{-1} $season^{-1}$	0.018 (0.02–0.08)	0.062 (0.03–0.13)	0.041 (0.02–0.14)	0.016 (0.01–0.10)
Dissolved P, μg P L^{-1} $season^{-1}$	51.8 (14–307)	16.4 (0.82–20)	23.6 (19–49)	20.7 (13–55)
pH	8.27 (7.7–9.1)	8.29 (6.4–10.0)	8.26 (7.6–9.5)	8.12 (7.5–8.8)
Specific electrical conductivity, μS cm^{-1} $season^{-1}$	431 (41–662)	440 (80–669)	422 (31–685)	518 (249–679)
Hardness, mg L^{-1} $season^{-1}$	137 (30 − 300)	132 (30–240)	120 (27–223)	172 (50–263)
Alkalinity, mg $CaCO_3$ L^{-1} $season^{-1}$	133 (21–304)	125 (23 − 221)	118 (13 − 322)	156 (62–214)
B. Water quantity				
Average amount of irrigation applied per event, mm	141		141	
Total amount of irrigation runoff, mm				
17 Jun	45		20	
24 Jun	13		9	
7 Jul	15		9	
21 Jul	13		6	
29 Jul	12		6	
5 Aug	32		8	

[a] Values inside parenthesis are computed ranges. Water quality characteristics such as pH, electrical conductivity, hardness and alkalinity are presented as means. Electrical conductivity values are reported at 25 °C.
[b] FT = Furrow tillage, CT = Conventional plow, URN = urea broadcast, UAN = 32% urea ammonium nitrate sidedressed.

(Table 3). Consequently, a large volume of overflow water directly influenced levels of N runoff during this irrigation event.

3.3. Seasonal N and P mass loads

Higher (P-value = 0.03) seasonal NH_4-N, NO_3-N, NO_2-N, and water P mass loads were estimated in CT treatments at both fertilizer N placements, with NO_3 being the largest among all nutrients measured (Fig. 5). Although flow-weighted nutrient concentrations were not different between tillage treatments (Fig. 4), total runoff volume across irrigation events were approximately 55% greater in CT than FT treatments. Since nutrient mass loads are influenced by runoff volumes (Pote et al., 1996; Sharpley et al., 1987), this relatively large volume of water and higher NO_3-N runoff significantly increased (P-value = 0.02) NO_3-N mass loads in CT treatments (Fig. 5). As more NO_3-N and irrigation water were lost through surface runoff, dissolved NO_3-N in runoff water and total irrigation water applied were significantly different (P-value = 0.03) between CT and FT treatments. Differences in runoff could have impacted lint production between CT and FT treatments (Fig. 2). Greater lint yields, in response to more available soil NO_3-N and irrigation water associated with conservation tillage, were also reported by Wright et al. (2007) and Bronson et al. (2001). The magnitude of NO_3-N runoff measured in this study was still below reported NO_3-N loads associated with tillage (Yoo et al., 1988; Harmel et al., 2006). In addition, the proportion of seasonal soluble N (NH_4, NO_3 and NO_2) in runoff water ranged from 0.09 to 0.34% of the total urea or UAN fertilizer applied, which is at the lower range of reported fertilizer N lost by others (Cessna et al., 2001; Lentz and Lehrsch, 2010).

Despite the relatively large proportions of runoff volume from CT fields, nutrient mass loads of NH_4-N, NO_2-N, and dissolved P were not significantly different between tillage treatments (CT vs FT) (P-value = 0.13–0.17) and among tillage and fertilizer N treatments (P-value = 0.27–0.80). Our results are contrary to those with greater NH_4-N and dissolved P levels in runoff associated with conventional tillage (Yoo et al., 1988; Soileau et al., 1994) or fertilization (Sharpley et al., 1987; Lentz and Lehrsch, 2010). In our study, the lack of tillage and fertilizer N response to NH_4-N, NO_2-N, and dissolved P runoff losses can be explained in several ways. First, the levels of NH_4 in surface runoff are highly related to the amounts of fertilizer applied (Sharpley et al., 1987; Bjorneberg et al., 2006). Application of fertilizer and tillage type did not increase NH_4-N and NO_2-N loads because N rates (101 kg N ha^{-1}) used in our study were below the recommended rate of 134 kg N, which are sufficient for optimal cotton growth and lint production (Main et al., 2013; Robertson et al., 2016), but not excessive to promote large N runoff losses at both tillage and N fertilizer placements. Secondly, while surface fertilization under conventional tillage (CT-

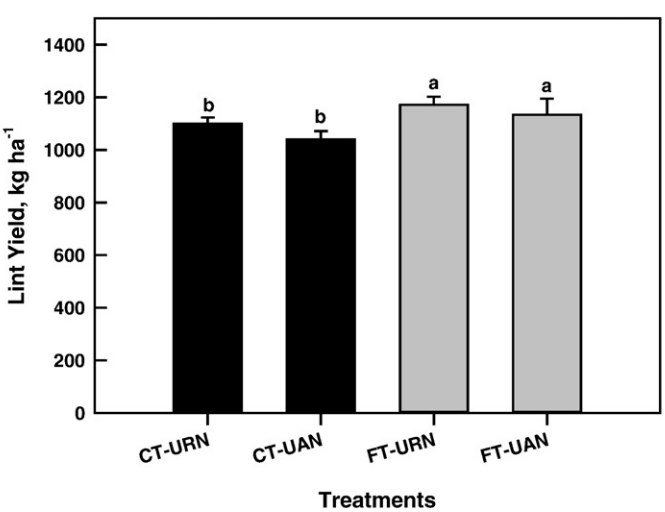

Fig. 3. Average lint yields in the different tillage and fertilizer N treatments (FT = Furrow tillage, CT = Conventional plow, URN = urea broadcasted, UAN = 32% urea ammonium nitrate injected). Lint yields followed by the same letter are not significantly different at P < 0.05.

Table 4
Median water quality characteristics of irrigation water used in the study.

Water quality metrics[a]	Irrigation water
Ammonium-N, mg N L^{-1}	0.157 (0.13–0.17)
Nitrate-N, mg N L^{-1}	0.168 (0.04–0.57)
Nitrite-N, mg N L^{-1}	0.030 (0.02–0.03)
Dissolved P, μg P L^{-1}	126 (56–196)
pH	7.45 (7.0–8.2)
Specific electrical conductivity, μS cm^{-1}	508 (300–697)
Hardness, mg L^{-1}	222 (216–227)
Alkalinity, mg $CaCO_3$ L^{-1}	195 (173–216)

[a] Values inside parenthesis are computed ranges and electrical conductivity values are reported at 25 °C.

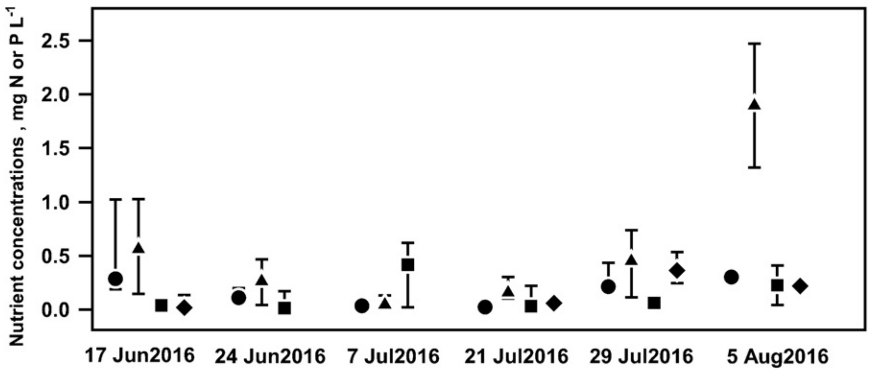

Fig. 4. Concentrations of soluble N and P during field runoff events. Scatter plots show medians for ammonium (●), nitrate (▲), nitrite (■) and dissolved phosphorus (♦) while error bars are 5th and 95th percentiles.

URN) enhances the potential for N losses by physically exposing fertilizer from flowing water, small increases in runoff losses were fairly insignificant to NH_4-N, NO_2-N and dissolved P mass loads when compared to FT treatment. Lastly, forms and transports of NH_4-N, NO_2-N and dissolved P are affected by many processes interacting in time and space. Ammonium is highly adsorbed in soil and, in most conditions, is transformed to NO_3 which can readily move with water. This transformation likely led to high NO_3 runoff potential instead of NH_4 observed in our study (Fig. 5). Nitrite, on the other hand, is an intermediary N and immediately converted to gaseous N compounds, such as NO and NO_2 via denitrification and nitrification processes in the soil (Van Cleemput and Samater, 1996). In our study, runoff NO_2-N level was minimal as well. In the case of dissolved P, the magnitude of runoff P is directly related to sediment concentration and/or extractable P in surface soil, such that when water flows on surface soil, P is either dissolved in water, desorbed or part of sediment in runoff (Westermann et al., 2001; Bjorneberg et al., 2006). In our study, the magnitude of runoff P remained mostly <5 g ha^{-1} $season^{-1}$ (Fig. 5), indicating either a small proportion of available P occurred in the soil or major form of runoff P occurred as sediment-bound. Unfortunately, sediment P was not measured in water samples in our study.

Overall, our results indicate the intensity and chemical form of seasonal nutrient losses were primarily controlled by amount of water runoff and agronomic practice. Since the source of N runoff mainly originated from N fertilizer, an increase in N rates will directly influence the amount of runoff N. These findings reiterate the necessity of applying fertilizer N according to crop nutrient requirements to eliminate excessive nutrient runoff. Also, the practice of optimal timing for termination of irrigation and frequency of irrigation events are effective ways to decrease amount of irrigation runoff, avoid water outflow, and at the same time retain, soluble nutrients in the field.

3.4. Other water quality characteristics of surface runoff

Across tillage and fertilizer N treatments, the variabilities observed for pH, electrical conductivity (EC), hardness and alkalinity in runoff water were generally small and their amounts were either below or within the ranges of water quality of irrigation water applied to the field (Table 4). Changes in water quality metrics during the growing period were not significant among the four treatments (P-value = 0.30–0.95). Magnitudes of runoff pH and EC were within the lower range of irrigation water quality hazard threshold and standards for streams suitable for growing cotton (MCES, 1990; APC and EC, 2015; Ayers and Westcot, 1976). Compared to other reports, mean EC values in our study were similar to the range of EC from wells sampled in the Sparta-Memphis aquifer, Arkansas in 2009 and 2011 monitoring years (Schrader, 2014). In addition, values of water hardness are mostly in the "hard" category and mean alkalinity values are classified as having a good buffering capacity (US EPA, 1994). Although levels of these water quality metrics showed minimal risk to growing crops and ecological health of waterways, water quality properties such as pH, hardness and alkalinity should be regularly monitored because of their influence on ecological health of surface waters, such as speciation and bioavailability of metals (i.e. uranium, copper, boron) in lakes and streams, which may lead to lethal concentrations to aquatic organisms (Markich, 2013; Linbo et al., 2009; Dethloff et al., 2009).

4. Conclusions

Results from this experiment indicated NO_3-N comprised the most losses in runoff water among nutrients measured and losses mainly occurred in CT treatments. Intensity of NO_3-N runoff losses was mainly influenced by volume of runoff water. Concentrations of other nutrients, such as NH_4-N and NO_2-N were low in runoff water and likely reflected reduced fertilizer loss. Dissolved P, even at the low concentration levels could potentially impact eutrophication in freshwater systems. However, the recent background nutrient limit set by US EPA for Ecoregion X (this includes Arkansas Delta where study was conducted) indicates the dissolved P values in this study are less likely to impair the quality of lakes and rivers. Other runoff water quality metrics such as pH, specific electrical conductivity, alkalinity and hardness were within levels that characterize irrigation water. Although concentrations of nutrients in

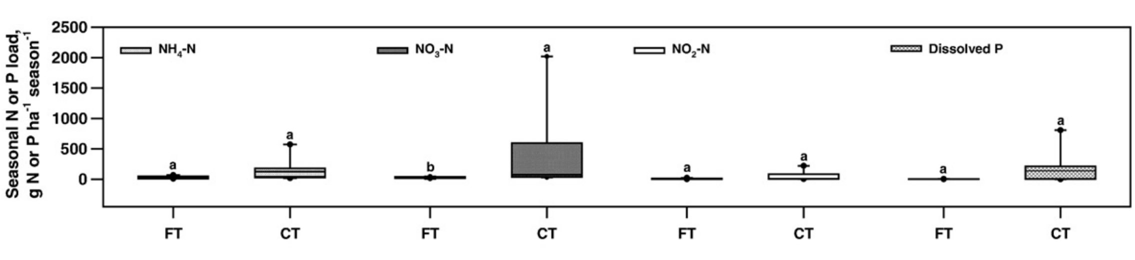

Fig. 5. Seasonal mass load of N and P in surface runoff associated with tillage practices (Furrow tillage: FT; Conventional tillage: CT). Box plots show median values while error bars are 5th and 95th percentiles. Within each nutrient mass load, tillage treatment followed by similar letter is not significantly different at P-level < 0.05.

runoff water were below risk levels, regular monitoring of these water properties is essential to prevent contamination off-site. Lint yields were more affected by tillage treatments. Our findings suggest nutrient runoff was mainly influenced by irrigation events. Improved irrigation management that minimizes nutrient runoff such as the use of timers to shutoff wells, computerized hole selection program, and optimal time to terminate furrow irrigation are some practices that avoid impactful water outflow. In addition, application of fertilizer within the ranges of crop nutrient requirement and planting cover crops during fallow periods are also strategies to minimize excessive nutrient losses.

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